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H_2 Formation in Low-Metallicity Galaxies

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ABSTRACT

A possible formation mechanism of hydrogen molecules on a galactic scale is examined. We are interested especially in the role of hydrogen molecules for the formation and evolution of primordial galaxies. Thus, the formation process of hydrogen molecules in a very low-metallicity galaxy (I Zw 18; the most typical metal-deficient galaxy) is studied. Adopting a recent observational result of the absorption lines of hydrogen molecules in I Zw 18, we obtain the upper limit for the ionization degree in the case where hydrogen molecules can form via the H^--process, although they are generally believed to form on the surface of dust grains. Furthermore, we present a critical ionization degree, above which the H^--process can be dominant over the formation process on the surface of grains. Interestingly, this critical ionization degree is comparable to the upper limit of the ionization degree for I Zw 18. For determining the formation process of hydrogen molecules, future observational facilities can be useful. Thus, we examine the detectability in some wavelengths for metal-deficient galaxies. According to our estimate, the near-infrared line emission of hydrogen molecules is observable at the level of 10 μJy, the free free radio emission is at the level of mJy, and the far-infrared emission from the dust on which hydrogen molecules form can also be detected at the 10-mJy level with its temperature of 16 K. The near-infrared line and the far-infrared continuum are feasible for ASTRO-F observations.

Subject headings: galaxies: dwarfs — galaxies: infrared — galaxies: ISM — ISM: dusts — ISM: evolution — stars: formation

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1. Introduction

How efficiently hydrogen molecules, H_2, form is the most important topic for theories concerning the formation of first-generation stars and primeval galaxies (e.g., Matsuda et al. 1969). This is because hydrogen molecules should become an important coolant in a metal-deficient gas cloud. A review article for such topics by the Japanese group is very useful for understanding the fundamental process in the formation of the first luminous objects via the formation of hydrogen molecules (Nishi et al. 1998). As found in that review paper, there have been many theoretical research projects for primordial hydrogen formation and the resultant effect. The metallicity effect is also given in Omukai (2000). Observationally, there is little evidence for hydrogen formation in primordial or very low-metallicity gas. In this paper, we thus propose an idea to resolve this observational weak point for a theory concerning the formation of primordial hydrogen molecules on galactic and subgalactic scales.

It is widely accepted that H_2 molecules are mainly formed on dust grains in metal-rich galaxies (e.g., Williams 1993; Herbst 1995; Takahashi et al. 1999). Low-metallicity galaxies, where only a little dust is expected to exist, are really important for our aim, since there is a chance for the formation of molecules via the so-called H^--process (Lequeux, Viallefond 1980; Jenkins, Peimbert 1997). This process is the following: H_2 formation starts with the formation of a negative ion, $\mathrm{H} + \mathrm{e} \rightarrow \mathrm{H}^- + h\nu$, where H is hydrogen, e is an electron, H^- is negatively and singly charged hydrogen, h is the Plank constant, and ν is the frequency of the photon emitted during H^- formation. That reaction rate is $1.0 \times 10^{-15}\, T_3 \exp(-T_3/7)$ cm^3 s^{-1}, where T_3 is the temperature in units of 10^3 K. This process is followed by the *faster* associative detachment reaction: $\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}$. Hence, the formation rate of H_2 is mainly controlled by H^- formation. In our estimate, hence, we regard the formation rate of H^- as the formation rate of H_2. Throughout this paper, we call this formation process of H_2 the H^- process.

While the reaction $\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}$ occurs, the photodetachment of H^- is also expected; $\mathrm{H}^- + h\nu \rightarrow \mathrm{H} + \mathrm{e}$. Indeed, the H_2 formation rate via the above process is $2 \times 10^{-9} n(\mathrm{H})$ s^{-1}, while that detachment occurs with a rate of 1.7×10^{-7} s^{-1} (Mathis et al. 1983). Thus, if the density of the interstellar medium is not very large (< 100 cm^{-3}), it is very difficult for H_2 to form via the H^--process. Furthermore, by mutual neutralization, the formation of H_2 can also be suppressed. That reaction is described as $\mathrm{H}^- + \mathrm{X}^+ \rightarrow \mathrm{H}_2 + \mathrm{X}$, where X is an arbitrary atom including hydrogen, and its reaction rate is $1.3 \times 10^{-7} T_3^{-0.5} X_\mathrm{e} n(\mathrm{H})$ s^{-1}, where X_e is the ionization degree of the interstellar medium (ISM), $n(\mathrm{H})$ is the number density of neutral hydrogen, and T_3 is temperature in units of 10^3 K. In the subsequent discussion, we can regard X_e as being much smaller than unity, and thus the latter process is slower than the photodetachment. Hence, we consider only the

photodetachment process against the formation of a hydrogen molecule via the H^--process.

In this paper, we discuss whether the H^--process for H_2 formation occurs in an observable low-metallicity galaxy. Our consideration will be useful for the theory of galaxy formation and first-generation stars when a metal-deficient galaxy is found to be a laboratory for H_2 formation via the H^--process. In section 2, we review an interesting observation of I Zw 18, which is the lowest known metallicity galaxy showing present star-forming activity. In section 3, we present an upper limit for the ionization degree, adopting the observational constraint of I Zw 18. If that upper limit is reached, the H^--process is expected to be the dominant process of H_2 formation in such a low-metallicity galaxy. In section 4, we give implications for future observations. Finally, we summarize this paper in section 5.

2. Observation of a Metal-Deficient Galaxy

Metal-deficient galaxies are suitable for our aim to find evidence of H_2 formation via the H^--process on galactic and subgalactic scales. The most typical and famous metal-deficient galaxy is I Zw 18. This is classified as a blue-compact dwarf (van Zee et al. 1998) and shows evident star formation. Importantly, I Zw 18 has the smallest abundance of heavy elements found in the ionized region in galaxies. Moreover, CO is not detected (e.g., Gondhalekar et al. 1998) in it. Although the latter does not always mean underabundance of C and O, it is just consistent with the metal-deficient property of I Zw 18. Hence, we regard this galaxy as being a typical metal-deficient galaxy. We note that I Zw 18 has another name, Mrk 116.

Recently, Vidal-Madjar et al. (2000) observed I Zw 18 by using the *Far Ultraviolet Spectroscopic Explorer*. Importantly, they did not succeed in detecting absorption feature of hydrogen molecules. Thus, the upper limit of the column density of hydrogen molecules is determined. That is, $N(\mathrm{H_2}) < 10^{15}$ cm^{-2}, where $N(\mathrm{H_2})$ is the column density of hydrogen molecules. Assuming the distance to I Zw 18 to be 11.5 Mpc, we adopt a size of I Zw 18, $R_{18} = 1.7$ kpc, which is proposed in van Zee et al. (1998). We can thus determine the upper limit of the number density of hydrogen molecules as being $n(\mathrm{H_2}) < 1.9 \times 10^{-6}$ cm^{-3}. In this paper, using this constraint for $N(\mathrm{H_2})$ and $n(\mathrm{H_2})$, we consider the formation mechanism of hydrogen molecules in a metal-deficient galaxy.

For our consideration in this paper, it is very important for us to estimate the strength of the radiation field of I Zw 18. According to figure 2 of Dufour et al. (1988), we find the observational flux at 1300 Å as being $\sim 2 \times 10^{-14}$ erg s^{-1} cm^{-2} Å^{-1}, which was determined by means of the *International Ultraviolet Explorer* satellite. The distance to I Zw 18 is assumed to be $\sim$ 10 Mpc and the size of of star-forming region of I Zw 18 to be $\sim$ 1

kpc. Both quantities were applied to find a rough estimate of the mean radiation field of I Zw 18. Adopting them, we found that the mean radiation field at the same wavelength is about $\sim 2 \times 10^{-8}$ erg s^{-1} cm^{-2} Å^{-1}, which is consistent to the radiation field adopted in Vidal-Madjar et al. (2000). In a recent work by Stasińska and Schaerer (1999), it has been confirmed. In addition, Stasińska and Schaerer have suggested that ISM in I Zw 18 can be clumpy, although the dense clumps have only a small volume filling factor. In the next section, we also consider a clumpy ISM whose clumps have a density of 100 cm^{-3} as suggested in Stasińska and Schaerer.

We can put a constraint on the star-formation history of I Zw 18 from the elemental abundance and ionization, both of which were measured in an H II region. Importantly, the expansion of super-bubbles can also affect chemical evolution, because newly synthesized elements are expelled to inter-galactic space (Martin 1996). This consideration has been developed further to other metal-deficient galaxies (Martin 1997). The effect of the outflow will be examined in a forthcoming paper. In the current paper, we try to connect the clumpiness of ISM and the intense radiation field, to reveal the formation processes of molecular hydrogens under the constraint given in Vidal-Madjar et al. (2000).

3. Upper Limit for the Ionization Degree

3.1. Assumptions

We consider the two branches for the formation of hydrogen molecules. As introduced in section 1, the first one is the H^--process. The second one is expected on the surface of dust grains (Hollenbach et al. 1971). We call the latter case the dust-process in this paper. Since we are interested in the H^--process, we examine the possibility of the H^--process in I Zw 18, which is a typical metal-deficient galaxy.

Here, we present our assumptions. Two important assumptions are employed: (i) The interstellar medium (ISM) is clumpy. The size of a typical clump is about 1 pc and its gas-number density is about 100 cm^{-3}. It is observationally believable for such a very small-scale structure to exist (e.g., Frail et al. 1994). To sum up, we are interested in a clumpy H I medium whose *mean* number density may be about 0.4 cm^{-3} (Vidal-Madjar et al. 2000). (ii) A steady state between the formation and destruction of hydrogen molecules is established. Hence, we estimate the number fraction of hydrogen molecules from an equilibrium condition. The number fraction of hydrogen molecules, $f(H_2)$, is defined to be the ratio of the number of hydrogen molecules to the total number of hydrogen nuclei. Although it may not be so significantly important, we state a third assumption: (iii) $f(H_2)$

is approximately $n(H_2)/n(H)$. This is very reasonable if most of the hydrogens are in the form of neutral hydrogen.

The first assumption makes it possible that the photodetachment process is suppressed. If we considered the condition of only the diffuse ISM, it would be found that the H^--process is not efficient owing to the photodetachment destruction of H^-. However, in the assumed clumps, the formation process of H_2 via the H^--process can occur faster than the photodetachment. If we adopt the Galactic condition, in each clump, whose size is about 1 pc, its A_V is estimated to be about 4. In such a condition, a standard PDR (photodissociation region) model predicts an ionization degree of $\sim 10^{-4}$ (Hollenbach, Tielens 1999). Someone might think that the Galactic values are inadequate for I Zw 18 owing to its metal deficiency. Fortunately, however, the lower metallicity condition for a fixed A_V is suitable for the larger size of the assumed clumps. When clumps with a fixed size of 1 pc exist in the low-metallicity condition, it is required that they have a large ionization degree. Then, our first assumption will be considered as a standard case when we consider whether the H^--process works or not.

We also comment on the volume fraction of the small clumps, $p_{\rm fr}$. If we assume that the interstellar gas is composed of clumpy and diffuse components, and that the density of the diffuse component is 0.1 cm^{-3}, we estimate $p_{\rm fr} \sim 0.003$ from the instant estimate of $0.1 \times (1 - p_{\rm fr}) + 100 \times p_{\rm fr} = 0.4$. Thus, if the mean density of the H I medium is 0.4 cm^{-3}, as given in Vidal-Madjar et al., the clump fraction is very small. Although our theoretical consideration is not altered as long as $p_{\rm fr}$ is much smaller than unity, the observational implications presented in section 4 are affected. Fortunately, I Zw 18 has a H I envelope, which is characteristic of blue compact dwarfs. In the H I envelope, $p_{\rm fr}$ could be on the order of 0.1. Then, the formation of H_2 would be observable in the H I envelopes of the blue compact dwarfs with metal deficiency.

The second assumption holds if the time-scale of gas consumption into stars is sufficient long. That is, the changing time-scale of the amount of heavy metal and dust is assumed to be longer than the interesting time-scale needed to establish equilibrium between the destruction and formation of molecular hydrogens. Since we are interested in the evolution of present-day galaxies, the time-scale of the variation of heavy metals and dust is approximately equal to the duration of star formation on a galactic scale. The variation time-scale for the star-formation rate may be about 10^9 yr (e.g., Legrand et al. 2000). Thus, the destruction time-scale and the formation time-scale of molecular hydrogens should be shorter than 10^9 yr. We confirm this point in the last paragraph of this section, since we need a quantitative definition for the formation and destruction of hydrogen molecules.

3.2. H^--Process

Here, we pay attention to the formation process via the H^--process. First of all, we examine the physical condition of clumps in which H_2 forms via the H^--process. The density and temperature are assumed to be 100 cm^{-3} and 100 K, respectively. Those parameters are taken from the observational indication of the cold atomic gas in the Galaxy (see Kulkarni, Heiles 1988; Dickey, Lockman 1990 for reviews). As long as the realistic condition of H I medium in I Zw 18 is in unclear, the adopted condition for the clumps is just the assumptions. By the way, that density is very interesting. This is because we can safely expect that H_2-formation via the H^--process against photodetachment occurs above a density of 100 cm^{-3}. That is, that density is also estimated from the reaction rates of the both processes presented in the third paragraph of section 1. Hence, we adopt a typical density of the clumps as being 100 cm^{-3} for a critical density.

Defining R_{H^-} to be the formation rate of hydrogen molecules in the dimension of cm^3 s^{-1}, we can estimate the formation rate of hydrogen molecules to be $2R_{H^-}n(H)n_e$, where n_e is the number density of electrons. For the convenience of subsequent sections, we rewrite the formation rate in terms of the ionization degree, $X_e = n_e/n(H)$; it then becomes $2R_{H^-}n(H)^2X_e$. In terms of the ionization degree, we can discuss a general condition of interstellar clouds, as found in the next section.

The destruction of hydrogen molecules is considered to occur efficiently owing to photodissociation. We thus estimate the destruction rate in the dimension of cm^{-3} s^{-1} as $I \times n(H_2)$, where I is the photodissociation rate. As a result, we adopt the following equilibrium condition for the above quantities:

$$I \times n(H_2) = 2R_{H^-}n(H)^2X_e, \tag{1}$$

that is,

$$f(H_2) = \frac{2R_{H^-}n(H)X_e}{I}. \tag{2}$$

As a destruction mechanism of molecular hydrogen, we assume photodissociation owing to massive stars. Since I Zw 18 shows evident star-forming activity, our assumption is reasonable. To make our presentation clear, moreover, we adopt the same radiation field of Vidal-Madjar et al. (2000). That is, $I = 4\times10^{-11}$ s^{-1} is employed. Importantly, the assumed clumps have an extinction of about $A_V \sim 4$. Then, the adopted I is rather overestimated for the destruction of H_2. In other words, the determined $f(H_2)$ is underestimated. Hence, even if our $f(H_2)$ is comparable to the limit for the H^--process to be active, we still expect that H_2 forms via the H^--process. Finally, we present only the conclusions with this constraint.

We should note that this photodissociation rate is expected near the O9.5 V star, i.e., ζ Oph (Jura 1974). This corresponds to the strength of the radiation field with an intensity of $G = 3\times10^{-8}$ photons cm^{-2} s^{-1} Hz^{-1} (i.e. 2×10^{-6} erg cm^{-2} s^{-1} Å^{-1}) at 1000 Å. We want to insist that since such an intense radiation field exists, hydrogens are partially ionized in the H I medium (e.g., Reynolds et al. 1998). If electrons originate from hydrogens, the electron number density is not so significantly small as that in the case of ionization of only the heavy elements (e.g., carbon). Therefore, if we considered the origin of electrons as only carbon, we would underestimate the number density of electrons. The formation rate of hydrogen molecules is estimated to be

$$R_{\mathrm{H}^-} = 1.0 \times 10^{-15} T_3 \exp(-T_3/7) \ \ \mathrm{cm}^3\ \mathrm{s}^{-1}, \tag{3}$$

where T_3 is the temperature in units of 10^3 K. For 100-K clumps, $R_{\mathrm{H}^-} = 1.0\times10^{-16}$ cm^3 s^{-1}.

From the above estimate, we can determine the fraction of molecular hydrogen, $f(\mathrm{H}_2)$, assuming the temperature of the gas clumps to be 100 K. Adopting the upper limit of the column density of hydrogen molecules and the typical column density of neutral hydrogen [$N(\mathrm{H}) = 2 \times 10^{21}$ cm^{-2}; Vidal-Madjar et al. 2000], $f(\mathrm{H}_2) < 10^{-6}$ is obtained. We thus find X_e to satisfy the following condition via equation (2):

$$X_\mathrm{e} < 2 \times 10^{-3} \times \left[\frac{10^2\mathrm{cm}^{-3}}{n(\mathrm{H})}\right]. \tag{4}$$

Since the upper limit of the left-hand side of equation (2) is provided by Vidal-Madjar et al. (2000) and section 2, we obtain the resultant upper limit for X_e for a given $n(\mathrm{H})$, which is estimated to be 100 cm^{-3} in inequality (4). This upper limit is allowed as long as the clumps are not very large.

We stress again that such partial ionization of hydrogens is possible, since there are ionizing stars in I Zw 18. By the way, we still do not judge whether the H$^-$-process works well in such a metal-deficient galaxy. Even if the ionization degree of I Zw 18 is estimated to be about the upper limit of the right-hand side of inequality (4), the dust process may be dominant over the H$^-$ process. Thus, we should examine whether the H$^-$ process really dominates over the dust process. We consider this topic in the next subsection.

3.3. Dust-Process

We know the formation rate of molecular hydrogen via the dust-process,

$$R_\mathrm{dust} = 10^{-17} \ \ \mathrm{cm}^3\ \mathrm{s}^{-1}. \tag{5}$$

This is the mean value expected in our Galaxy and found by Jura (1974) to be an upper limit. The equilibrium state becomes

$$I \times n(\mathrm{H_2}) = 2R_{\mathrm{dust}} n(\mathrm{H})^2 \frac{\mathcal{D}}{6 \times 10^{-3}}, \tag{6}$$

that is,

$$f_{\mathrm{dust}}(\mathrm{H_2}) = \frac{2R_{\mathrm{dust}} n(\mathrm{H})}{I} \frac{\mathcal{D}}{6 \times 10^{-3}}. \tag{7}$$

Here, $\mathcal{D}$ is the dust gas ratio in mass and the displayed quantity of $\mathcal{D}$ in equations (6) and (7) is the Galactic value (Spitzer 1978).

We wish to note that $f_{\mathrm{dust}}(\mathrm{H_2})$ depends on the dust-gas ratio. That is, if there were no dust in interstellar space, $f_{\mathrm{dust}}(\mathrm{H_2})$ would always be zero. Considering the dust-process, Vidal-Madjar et al. (2000) have estimated another upper limit of the column density of hydrogen molecules that satisfies their own observational constraint. In this meaning, their discussion is consistent. In this paper, we undertake another discussion by using the same observational constraint.

Here, we examine the condition that the $\mathrm{H^-}$-process is dominant over the dust process. Equating the left-hand sides of equations (1) and (6), we determine a critical ionization degree of X_{ec} with values of $R_{\mathrm{H^-}}$ and R_{dust},

$$X_{\mathrm{ec}} = 1 \times 10^{-1} \times \left(\frac{\mathcal{D}}{6 \times 10^{-3}} \right). \tag{8}$$

If $X_{\mathrm{e}} > X_{\mathrm{ec}}$, the $\mathrm{H^-}$-process dominates over the dust-process for a given radiation field. If not, the dust-process is the dominant formation process of hydrogen molecules. Thus, we present the first conclusion as follows. Assuming $\mathcal{D}$ to be about 10^{-4} in I Zw 18 (about 1/50 of the Galactic value), X_{ec} is estimated to be 2×10^{-3}. We have already obtained the upper limit of X_{e} of I Zw 18 in equation (4) as 2×10^{-3} for $n(\mathrm{H}) = 100\ \mathrm{cm^{-3}}$. This upper limit is comparable to X_{ec}. This means that the $\mathrm{H^-}$-process is expected to occur in the small H I clumps in I Zw 18 if the upper limit of X_{e} is reached.

Before closing this section, we examine whether an equilibrium state is established well on a typical time-scale of galaxy evolution. The destruction time-scale of $\mathrm{H_2}$ is about $I^{-1} \sim 10^3$ yr. As long as equations (1) and (6) are adopted, the formation time-scale should also be of the same order of magnitude due to the definition of equilibrium. Fortunately, the evolution time-scale (i.e., time-scale of metal enrichment) of star-forming galaxies is $> 10^9$ yr (e.g., Legrand et al. 2000). Thus, our steady state assumption is reasonable for our research.

4. Observational Implication

4.1. H_2 Emission Line in the Near Infrared

Observations of the H_2 rotational and vibrational line emissions are important to show the formation of molecules in clumps, as assumed in section 3. Here, we adopt the model of photodissociation regions by Black and van Dishoeck (1987). To be consistent with the density and temperature adopted in section 3, we adopt Model 1, whose physical parameters are listed in their table 1. [It is assumed that $n(H) = 1.0 \times 10^2$ cm^{-3} and $T = 100$ K. For the ultraviolet flux, $G \sim 2 \times 10^{-6}$ erg cm^{-2} s^{-1} Å^{-1}, which is comparable to that at ζ Oph, is adopted (section 3.2).] From their tables 1 and 2, we see that the intensity of the line at 2.406 μm is $I_{2.4} = 9.0 \times 10^{-8}$ erg s^{-1} cm^{-2} sr^{-1}. We have chosen this line because it is the strongest.

We estimate the flux detected on the earth, $f_{2.4}$ (erg s^{-1} cm^{-2} Hz^{-1}). This is estimated to be

$$f_{2.4} = \frac{I_{2.4}\Omega}{\Delta\nu}, \tag{9}$$

where Ω and $\Delta\nu$ are the solid angle of the object and the typical width of the wavelength band. For a particular interest in metal-deficient galaxies, we estimate the flux for I Zw 18, whose distance is assumed to be 11.5 Mpc and the typical radius for the gas envelope is 1 kpc (i.e., $\Omega = 2.5 \times 10^{-9}$).

To determine $\Delta\nu$, we specify the observational facility if the wavelength resolution is larger than the typical broadening of the line. Here, we estimate the detectability by ASTRO-F. ASTRO-F is planned to conduct deep imaging in the near-to-mid infrared range by the infrared camera (IRC; http://www.ir.isas.ac.jp/ASTRO-F/index.html; Shibai 2000; Onaka 2000).[3] The wavelength resolution at near infrared (NIR) is $\nu/\Delta\nu \sim 40$. Thus, at 2.4 μm, $\Delta\nu \sim 3 \times 10^{12}$ Hz. Since this is much larger than the typical broadening ($\sim 4 \times 10^9$ Hz for the velocity dispersion of 10 km s^{-1}), the line width is determined by the resolving power. Adopting $\Delta\nu \sim 3 \times 10^{12}$ Hz, we obtain $f_{2.4} \sim 8$ μJy (1 Jy $= 10^{-23}$ erg s^{-1} cm^{-2} Hz^{-1}). Since the detection limit of IRC is ~ 10 μJy, it may be marginally possible to detect the NIR line of H_2 molecules. The molecules may suffer stronger ultraviolet (UV) radiation if they exist near star-forming regions. If Model 2 of Black and van Dishoeck (1987) is adopted, where the UV intensity is 30-times larger than that in Model 1, we obtain $f_{2.4} \sim 50$ μJy ($I_{2.4} = 5.7 \times 10^{-7}$ erg s^{-1} cm^{-2} sr^{-1}). In this case, the line will be easily detected by future observations. However, we should note that if the covering factor of the H_2 molecule is much

[3]ASTRO-F will also make an all-sky survey in the far infrared.

smaller than unity, the detection becomes difficult. In summary, the detection of the H_2 molecular line from I Zw 18 by ASTRO-F indicates that the covering factor of the molecule is not much smaller than unity and that the UV radiation field is stronger than the value for ζ Oph. As already commented in subsection 3.1, we predict that such H_2 emission is observed in the H I envelopes of metal-deficient blue compact dwarf galaxies around the periphery of the star-forming region and/or at the inner edge of the H I envelope.

However, if the line-to-continuum ratio might be so distinct, greater spectroscopic resolution will be needed to find the line emission of molecular hydrogen in I Zw 18. In this meaning, the IRCS instrument on board the SUBARU telescope may be useful, while if the expected surface brightness is very small ($\sim 0.5\ \mu$Jy arcsec^{-2}), the current observational facility will have difficulty to observe it. If it is observed, the hydrogen formation will be enhanced by the dust. This will constrain the dust evolution model of dwarfs (Hirashita 1999).

4.2. Radio Continuum

If the ionization degree is large (e.g., $X_{\rm e} > X_{\rm ec}$), we may expect the radio free free emission from H I envelopes of the metal deficient galaxies. Someone might think that the contamination of electrons in the star-forming region of I Zw 18 exists. We admit that difficulty. Fortunately, however, I Zw 18 is a blue compact dwarf galaxy, which is often associated with an extended H I envelope. Indeed, such an envelope is observed around I Zw 18 (Lequeux, Viallefond 1980). Thus, we pay attention to the free free radiation from the H I envelope of I Zw 18. Of course, it is only partially ionized owing to its central radiation field and stars in the H I envelope, itself, although we do not know the exact ionization degree of the H I envelope at this moment.

The emissivity of the free free emission is

$$\begin{aligned}\epsilon_\nu^{\rm ff} &= 6.8\times 10^{-38}\quad {\rm erg\ cm^{-3}\ s^{-1}\ Hz^{-1}}\\ &\times n_{\rm e} n_{\rm i} T^{-0.5} \exp\left(-\frac{h\nu}{k_{\rm B}T}\right),\end{aligned} \tag{10}$$

where $n_{\rm i}$ is the ion number density, and $k_{\rm B}$ is the Boltzmann constant (Rybicki, Lightman 1979). The Gaunt factor is estimated to be of order unity. First, we treat a diffuse media. Since the ionization of hydrogen is assumed to be dominant over the other species in the supply of electrons, $n_{\rm i}$ is estimated to be about $n_{\rm e}$. We adopt $n_{\rm e}$ as being about $n({\rm H})X_{\rm ec} = 8\times 10^{-4}\ {\rm cm^{-3}}$ for $n({\rm H}) \sim 0.4\ {\rm cm^{-3}}$, we find it for a radio wavelength ($h\nu \ll k_{\rm B}T$),

$$F_\nu^{\rm ff} \sim 1\times 10^{-10}\ {\rm Jy}, \tag{11}$$

where F_ν^{ff} is the flux of free free emission in the electron temperature of 7000 K. We assume the size of the H I envelope to be 2 kpc (i.e., $> R_{18}$) and the distance to I Zw 18 to be 11.5 Mpc. The flux level is impossible to detect it, since at most mJy flux will be observable by means of observational facilities in the near future.

The above estimate has been applied to a diffuse medium. Next, we consider the clumpy H I medium in a consistent way with the previous sections. Interestingly, such dense clouds can form in the H I envelope (e.g., Saitō et al. 2000). That is, there may be a significant amount of dense clouds in the H I envelope. To make the situation simple, almost all hydrogens are hypothesized to become dense clouds in the H I envelope. In such a case, we expect the free free radiation in a radio band to be on the order of 10 mJy, adopting $n(\mathrm{H}) = 10^2$ cm^{-3}, $X_{\mathrm{e}} \sim 2 \times 10^{-3}$, and $T = 100$ K. Thus, we suggest that if intense free-free emission is observed in the HI envelope, we can expect that hydrogen molecules form in clumps in that envelope via the H$^-$ process. To justify this, of course, we should determine the amount of dust in the H I envelope, since it is necessary for $\mathcal{D}$ to be very small. We then discuss the observational feasibility in the far-infrared (FIR) band, where the thermal emission of dust has a peak intensity, in order to constrain the effectiveness of the H$^-$ process in metal-deficient galaxies.

4.3. Far-Infrared Band

Here, we examine the observational feasibility in the FIR band. To be consistent with the above sections, we set the dust-to-gas ratio in I Zw 18 as $\mathcal{D} = 10^{-4}$. If the FIR radiation is not detected with the level of the result later, the dust-to-gas ratio should be less than 10^{-4}. In such a case, X_{ec} becomes lower, and the possibility that the H$^-$-process is dominated over the dust-process becomes higher. Other parameters are selected as follows: the *mean* number density of hydrogen is 0.4 cm^{-3}, and the typical radius of the H I envelope is 1 kpc. We note that both of the parameters are consistent with the above discussions.

Adopting the above parameters, we estimate the total mass of dust in I Zw 18 to be $M_{\mathrm{dust}} \sim 8 \times 10^3 M_\odot$. Lonsdale Persson and Helou (1987) related M_{dust} and f_ν (the flux of the dust emission at the frequency of ν) as

$$f_\nu = \frac{K_\nu M_{\mathrm{dust}} B_\nu(T)}{D^2}, \tag{12}$$

where K_ν is the emissivity of dust per mass, $B_\nu(T)$ is the Planck function, and D is the distance to I Zw 18. They also estimated K_ν at a wavelength of 100 μm as 90 cm^2 g^{-1} based on Draine and Lee (1984). The dust temperature and the distance are assumed to be 16 K and $D = 11.5$ Mpc, respectively (Vidal-Madjar et al. 2000). With these values, we obtain f_ν

at 100 μm as 7 mJy. This flux level will be marginally observable with future space missions, such as ASTRO-F (in the pointing mode; detailed information of this mission is available in http://www.ir.isas.ac.jp/ASTRO-F/index-e.html.) and SIRTF (Bicay, Werner 1998). The future infrared facilities are summarized in Appendix of Takeuchi et al. (1999).

The temperature of 16 K is a conservative value based on the assumption that dust is heated by the mean interstellar UV radiation field (Vidal-Madjar et al. 2000). If dust exists near star-forming regions, the temperature should be higher. If the radiation field is 30-times larger than that estimated in Vidal-Madjar et al. (2000), the dust temperature becomes $T = 23$ K. In this case, we obtain f_ν at 100 μm as 100 mJy and the detection becomes easier. Thus, the flux is strongly sensitive to the dust temperature. The temperature should also be determined from multi-band photometry by ASTRO-F.

5. Summary

We have examined the expected upper limit of the ionization degree in the most metal-deficient galaxy, I Zw 18, while adopting the recent data provided by Vidal-Madjar et al. (2000). Moreover, we present a critical ionization degree above which the H^--process can be dominant over the formation process on the grain surfaces. This critical ionization degree is comparable to the upper limit of the ionization degree ($\sim 2 \times 10^{-3}$). We thus expect that the H^--process works for the formation of H_2. At least, both the H^--process and the dust-process can work together. In order to obtain further constraint on the formation process of H_2, we estimated the flux of the NIR H_2 emission line, free-free radio emission, and a FIR dust continuum. The flux level of the H_2 line emission is 10 μJy, which is detectable by ASTRO-F. If there are many HI clumps in the H I envelope, we may detect the free-free emission of the free electrons in the radio bands. Furthermore, the FIR continuum emission is also detected by ASTRO-F with a 10 mJy level if the dust-to-gas ratio is about 1/50 of the Galactic value. If the FIR flux is below this level, the dust-to-gas ratio may be smaller than 1/50 of the Galactic value and the lower bound of the ionization degree for the dominant H^--process is lowered (i.e., the possibility that H^--process is the dominant process for the H_2 formation becomes higher).

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